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Future Directions in Aeropropulsion Technology

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FUTURE DIRECTIONS IN AEROPROPULSION TECHNOLOGY

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SUMMARY

It is the purpose of this paper to discuss future directions in aeropropulsion technology that have been identified in a series of studies recently sponsored by the U.S. Government. Advanced vehicle concepts that could become possible by the turn of the century are presented along with some of their projected capabilities. Key "building-block" propulsion technologies that will contribute to making these vehicle concepts a reality are discussed along with projections of their status by the year 2000. Some pertinent highlights of the NASA aeropropulsion program are included in the discussion.

INTRODUCTION

As we approach the 50th anniversary of the first successful demonstration of a turbine engine, it's appropriate that we pause and reflect upon the impact of that remarkable achievement and the notable aeropropulsion technology advances that have been made since then. Frank Whittle's achievement laid the foundation for our current air transportation system. And even though Whittle was a true visionary, it is likely that today's turbine-powered aircraft fly much faster, higher, and farther than he could have ever imagined in the late 1930's. All of this can be directly attributed to the significant gains made in aeropropulsion technology during the intervening years. Major advances in turbomachinery and materials have been key to achieving significant increases in both propulsive and thermal efficiencies of turbine engines. Also, improved understanding of internal aerodynamics, combustion kinetics, heat transfer, and structural dynamics have all played major roles in achieving these gains. As a result, today's aircraft engines are approaching a paragon of sophistication for complex mechanical systems.

From this high level of success, we need to turn our attention toward defining the future directions of aeropropulsion technology. The prime questions that need to be addressed are:

(1) Has aeropropulsion technology reached a level of maturity that severely limits significant future advances?

(2) If not, what are the prime opportunities for achieving major advancements in aeropropulsion technology to position the aeronautics industry for the 21st century? The U.S. Government has recently sponsored a series of studies (conducted both internally and externally) to address these issues.

The President's Office of Science and Technology Policy (OSTP), after conducting an extensive study of the future of aeronautics (ref. 1) stated that there still existed a large potential for technology improvements in aeronautics and that advanced aeropropulsion technology is a key element. To

provide a basis for planning future aeronautical research and technology programs, NASA requested the National Research Council to conduct a workshop in order to project what the state of technology could be in the year 2000. Experts from government, industry, and universities were organized into eight panels in the technology areas of: aerodynamics; propulsion; structures; materials; guidance, navigation and control; computer and information technology; human factors; and systems integration. After the "Aeronautics 2000" panels made their technology projections (ref. 2) a Vehicle Applications Panel projected advanced types of aeronautical vehicles that could evolve from the advanced technologies (ref. 3). As a result, advancements in propulsion technology were identified that were not only possible with continued effort, but that were essential for the majority of advanced vehicle concepts. Also, this Vehicle Applications Panel reported that "propulsion is the pivotal and pacing technology" for development of most of the advanced aircraft concepts considered.

Guided by these studies, input from Congressional advisory panels, and internal strategic planning, we at NASA Lewis have recently restructured our efforts toward an aggressive aeropropulsion technology program aimed at future propulsion opportunities. Key "building block" disciplines were identified, and research efforts in these areas were consolidated and redirected. Particular propulsion systems or vehicles now provide the focus for more specific technology efforts. These elements, which comprise the NASA Lewis aeropropulsion program, are all consistent with recommended future directions identified by the "Aeronautics 2000" technology and vehicle panels. As such, they address the National Aeronautical R&D Goals recently proposed by the OSTP Aeronautical Policy Review Committee (ref. 4) and endorsed by the Science Advisor to the President.

It is the purpose of this paper to discuss these future directions in aeropropulsion technology. Advanced vehicle concepts that were identified as being possible by the turn of the century will be presented along with some of their projected capabilities. Key propulsion technologies that will contribute to making these vehicle concepts a reality will be discussed along with projections of their status by the year 2000. Some pertinent technology highlights of the NASA aeropropulsion program will be included in the discussion.

ADVANCED VEHICLE CONCEPTS

It is possible to conceptualize how technology advancements anticipated to occur by the year 2000 could be utilized to provide advanced aeronautical vehicle systems. This assessment was performed in a preliminary manner by the systems integration panel of the "Aeronautics 2000" Workshop (ref. 2) and then to a greater depth by the follow-on Vehicle Applications Panel (ref. 3). Advanced vehicle concepts identified as providing either new capabilities or very significant fuel savings are indicated in figure 1, and their capabilities and propulsion requirements are discussed herein. As seen, the full spectrum of flight from low subsonic to orbital is covered. Where pertinent, vehicle-focused NASA engine system programs are included in the discussion.

Subsonic Vehicles

The subsonic vehicle examples indicated in figure 1 are subsonic transports, rotorcraft, commuter/general aviation aircraft, and extremely high altitude aircraft. From a propulsion viewpoint, subsonic transports have received the greatest attention in the past because these are key to our air transport industry. As such, the technology levels in transport engines are probably the most advanced of this group. In the future, as stated by one of the recently proposed National Aeronautical R&D Goals (ref. 4), these advanced aeropropulsion technology levels need to be not only further advanced but to be transferred to smaller engines for rotorcraft and commuter/general aviation aircraft. And in the longer term, high altitude aircraft for special purposes offer potential for the application of very unique technologies to propulsion systems.

Subsonic transport. - Because of the wide range of requirements, a variety of subsonic transport concepts are being investigated for application into the twenty-first century. Conventional (nongeared) turbofans, geared turbofans, gearless pusher turboprops, and geared tractor and pusher turboprops are among the propulsion systems under consideration. For these engines, compressor pressure ratio has increased linearly for the past 30 yr and is expected to continue the same trend. For commercial engines, there is little incentive to greatly increase the turbine temperature. Figure 2 illustrates a civil pas- senger transport powered by advanced counter-rotating turboprops, which will have high efficiency and low noise. Fuel usage with these engines will be significantly less than that of today's turbofan fleet. The aircraft will provide a high level of ride comfort through automated flight controls at low altitudes. It will also be capable of operating at speeds comparable to those of current subsonic jets.

The NASA Advanced Turboprop (ATP) Program is a cooperative government-industry effort directed at developing an advanced technology base for highly-loaded, multibladed propellers for use at Mach 0.65 to 0.85 and at altitudes compatible with the air transport system requirements. Advanced turboprop engines offer the potential of 15 to 30 percent savings in aircraft block fuel usage relative to advanced turbofan engines (50 to 60 percent savings over today's turbofan fleet). The program to develop the technologies needed to implement this potential fuel savings (and an accompanying 7 to 15 percent operating cost advantage) consists of both small-scale model testing and analytical technology efforts as well as a test program to evaluate large-scale hardware. The ATP program objectives, goals, and benefits are shown in figure 3. Both single-rotation (SR) and counter-rotation (CR) turboprop systems are included. In the counter-rotation area, both geared systems and a unique gearless pusher configuration are being pursued.

The analytical and subscale model experimental effort includes investigations in the areas of propeller aeroperformance, aeroelasticity, and acoustics; installation aerodynamics; cabin environment; and systems integration and benefit assessment. Advanced gearbox technology will also be investigated through a program consisting of design studies and component testing. In the area of propeller technology, several 2-ft diameter single-rotation propeller models have been wind tunnel tested, and the results established the potential to achieve propulsive efficiencies greater than 80 percent using thin, highly-swept blades. Figure 4 is a collage of photographs showing three eight-bladed and two ten-bladed configurations

(single rotation) that were wind tunnel tested to determine the effect of blade sweep and blade count on efficiency and source noise. In addition, some models were mounted atop a JetStar aircraft fuselage and flight tested at the NASA Dryden Flight Research Facility to acquire both farand near-field noise data.

A major focus of the ATP Program is the design, fabrication, and test of an eight-bladed, 9-ft diameter, single-rotation turboprop, a mock-up of which is shown in figure 5. The tests will evaluate the structural, aeroelastic, and acoustic characteristics of large-scale thin swept blades. These characteristics cannot be reliably scaled at the present time from model to large-size. This large-scale effort, which is needed to validate the design of the advanced blades and provide data for the improvement of the analytical prediction capability, will involve both ground and flight testing. The flight test vehicle will be a modified Gulfstream II aircraft with the turboprop propulsion system mounted on one wing in a tractor-type installation as shown in figure 6. In addition to providing turboprop structural and near-field acoustic data, the flight test will also provide needed data on cabin interior noise levels.

Counter-rotation propellers, which can result in improved propeller efficiency due to elimination of the swirl component of the discharge velocity, are also being studied. The major part of this effort involves a unique counter-rotation turboprop propulsion system (fig. 7), referred to as the "UnDucted Fan" or simply the UDF, which is also being evaluated in large scale through both ground and flight tests. This concept is unique in that the gearbox has been eliminated and the propeller blades are driven directly by a counter-rotating power turbine which has no interstage stator vanes. The development of the large-scale UDF propulsion system is supported by an extensive model program to verify the aerodynamic and aeroelastic performance and determine the aeroacoustic characteristics of the counter-rotating propellor blades.

A parallel geared counter-rotating turboprop effort is being conducted based on experience gained in the single-rotation program. Counter-rotation propeller models will be wind-tunnel tested on a propeller test rig and evaluated to determine their aerodynamic performance, as well as their acoustic and aeroelastic characteristics. Parallel with this, counter-rotation gearbox technology will be advanced. A geared counter-rotation turboprop propulsion system data base will thus be established.

Commuter/general aviation aircraft. - Future commuter aircraft represent a special challenge. Fuel cost has become the largest portion of DOC (over 50 percent) for most commuters. Therefore, fuel efficiency is the prime characteristic of interest, with acquisition and maintenance costs also being important drivers. Spare parts/engines are not stocked to the same extent as for large trunk airlines; therefore, reliability is a critically important factor. Impeding the achievement of high reliability is the short stage-length these aircraft generally fly. This results in a high number of engine cycles per flight hour and a severe operating environment for the engines.

Future engines for commuter and general aviation aircraft will include: advanced versions of conventional turbine engines; unconventional turbine

engines incorporating such features as regeneration and/or ceramic hot-section components; and, for the smaller power levels, intermittent-combustion (IC) engines. The potential improvements in cycle efficiency attributable to regeneration and/or ceramics are shown in figure 8. Obviously, the use of ceramics and/or regenerators offer potential for significant benefits for future engines.

These turbine engines are in the "small engine" class and make use of components such as centrifugal compressors, radial turbines, and reverse flow combustors, all of which will benefit from evolutionary technology improvements. Compressor and turbine efficiencies in these smaller engines should approach those of the larger machines. As illustrated in figure 9, centrifugal compressor efficiency decreases with decreasing engine size, but the advanced technology improvements are expected to significantly reduce the size penalty. Temperatures in these engines will approach 2500 °F. Nonmetallic materials will be in greater use throughout the engine.

Two promising intermittent-combustion engine concepts are a high-speed stratified-charge rotary engine and a two-stroke radial diesel engine, both of which have multifuel capability and could readily burn turbine fuel. Both are relatively lightweight, very efficient, compact, and smooth running. One rotary engine concept currently being studied involves a turbocharged multi-rotor stratified-charge combustion engine. This engine, shown in figure 10, incorporates thermally-insulated combustion-chamber faces as well as exhaust gas passages to reduce waste heat loss. A promising diesel engine concept involves a two-stroke radial cylinder configuration. The cylinders are insulated to reduce heat loss and cooling requirements. This engine is turbo-compounded to recover the energy in the exhaust gases and feed that energy into the propeller gear train. Advanced ceramic or refractory metal technology will be needed to provide the insulating materials for thecombustion chambers. The use of advanced composites and high-strength materials will be required in other parts of the engine to reduce weight.

<u>Rotorcraft</u>. - Rotorcraft cover a broad range of vertical lift aircraft including next-generation conventional helicopters, large passenger/cargo aircraft, and advanced high-speed vehicles. In general, higher performance and reductions in noise and vibration are the key future design drivers. For the next generation of rotorcraft, new technology will provide vehicles with high productivity, better fuel economy, larger payload-to-weight ratios, longer range, better ride, and lower noise generation than current rotorcraft. The new rotorcraft will also have all-weather flight capability which will be dependent upon highly advanced electronic control systems.

Future engines for next-generation helicopters will include advanced conventional turboshaft engines and unconventional turboshaft engines incorporating such features as regeneration and/or ceramic hot-section components. These unconventional engine features can provide significant improvement in cycle efficiency as previously shown in figure 8. All conventional components in these engines should benefit from "small engine" evolutionary technology improvements. As nonmetallic materials (primarily ceramics) come into greater use, these engines will also benefit from increasing turbine temperatures. In addition to advanced turbine engines, advanced rotary and/or diesel intermittent-combustion engines should be available. Major fuel savings, as indicated in figure 1, will be the prime benefit provided by these future engines for next-generation conventional rotorcraft.

The high-speed rotorcraft of the future will provide speed, range, and endurance capabilities beyond those of conventional helicopters. The unique features of these aircraft, several concepts for which are illustrated in figure 11, will enable these vehicles to operate in forward flight like conventional subsonic cruise aircraft and still retain vertical takeoff and landing capability. One of the essential technologies for high-speed rotorcraft is the "convertible" engine, which can operate as a turboshaft engine during vertical flight and as a turbofan (or turboprop) engine during cruise.

An initial version of a "convertible" engine is currently being tested at NASA Lewis (fig. 12). This test vehicle uses a full-scale 5000-horsepower TF-34 engine with variable inlet vanes in the fan duct to convert between turbofan and turboshaft operating modes. The vanes would be open during cruise and closed during vertical flight when the rotor is clutched into the engine. During the last year, this engine has been run successfully in both fan and shaft modes as well as through the conversion between modes in both directions.

Extremely high altitude aircraft. - Projected future needs include aircraft to collect atmospheric samples, function as alternatives to satellites, and support search and rescue activities. These needs for extremely high altitude aircraft may promote development of a new unique class of unmanned aircraft that will be powered by either turbine/intermittent-combustion engines or unique noncombustion propulsion systems. For the combustion engines, the cycle will have to be tailored for high altitude operation. For example, regenerators may be used on turbine engines to improve the performance/efficiency characteristics. Alternatively, high-pressure-ratio turbochargers would be required for intermittent-combustion engines in order to maintain power up to high altitudes. Advanced ceramic materials would probably be required for either intermittent-combustion engines to reduce the cooling requirements or for turbine engines to permit increased turbine temperature levels.

Missions of very long duration (more than one week) require revolutionary propulsion concepts consisting of large diameter propellers driven by electric motors. These electric motors could be powered by solar or beamed microwave energy. An example of a solar-powered aircraft is illustrated in figure 13. Advanced electric motors with high efficiency and low specific weight would be required for this application. A solar-powered aircraft would require very-high-efficiency energy storage capabilities. Beamed microwave systems would require transmitters and rectennas that could operate at low conversion losses. Lightweight materials would be needed in all areas of the propulsion system.

Supersonic Vehicles

Supersonic vehicle examples highlighted by the "Aeronautics 2000" Vehicle Applications Panel, as indicated in figure 1, are the sustained supersonic cruiser, the supersonic transport, and the supersonic short takeoff-vertical landing (STOVL) aircraft. One of the recently proposed National Aeronautical R&D Goals (ref. 4) is to develop the technology for efficient, long-distance supersonic cruise capability for military and civil aircraft. This encompasses the sustained supersonic cruiser and the supersonic transport. In the area of

supersonic STOVL aircraft, the United States and the United Kingdom are developing plans for possible future collaboration on advanced STOVL technology.

Sustained supersonic cruiser. - A future sustained supersonic cruiser, as illustrated in figure 14, would be expected to cruise at Mach numbers approaching 3.5 and at altitudes in excess of 70 000 ft. Ideally, it will be desirable to maneuver at 2 g's at this cruise condition. At lower supersonic speeds and altitudes, maneuvering at 4 to 5 g's might be required. Improved operating efficiency would allow a flight radius of 1000 n mi. The realization of these flight characteristics will depend on the development of advanced airframe materials and structures that can withstand sustained temperatures of 1000 °F in critical areas such as leading edges, inlets, and nozzles.

The propulsive system for this type of aircraft could be a compound-cycle ramjet/turbojet, a low-bypass-ratio double-bypass-engine, or an afterburning turbojet. Turbine inlet temperatures would have to be well above 3000 °F, and overall engine pressure ratios of up to 16 (compared with present values of 8) would have to be achieved (preferably in one spool). High unaugmented specific thrust would be required for efficient cruise with the afterburner used only for acceleration and high maneuverability.

Supersonic transport. - An advanced supersonic transport would be expected to achieve three times the productivity of a similarly-sized subsonic airplane while burning slightly less than twice as much fuel. It would cruise at speeds up to Mach 3.2 over ranges approaching 5500 n mi while carrying as many as 600 passengers. Advanced supersonic transport aircraft concepts are illustrated in figure 15.

The development of the future supersonic transport requires improved propulsion systems for reduced fuel consumption and low noise, increased laminar flow to reduce cruise drag, reduced structural weight to improve payload to weight ratios, and reduced manufacturing costs. To provide fuel efficient operation for both supersonic and subsonic cruise, variable-cycle engines are required. Combustor exit temperatures would be on the order of 3000 °F. Variable geometry with reduced complexity will be essential for the compressor and turbine stators, inlets, nozzles, and mixers.

Supersonic STOVL. - An illustration of a potential supersonic short takeoff-vertical landing aircraft (STOVL) is shown in figure 16. This advanced STOVL aircraft would be expected to operate from short or damaged runways or from ships. Speed capabilities up to cruise Mach numbers of 2.0 to 2.5 could be required for future military missions. Four propulsion concepts that are currently being considered for supersonic STOVL are shown in figure 17. They are:

(1) Remote Augmented Lift System (RALS), which ducts the fan air ahead of the fan and augments the fan thrust by burning (fig. 17(a)).

(2) Deflected Thrust System, which uses separate fan and core flow, swiveling nozzles, and fan air burning for supersonic flight (fig. 17(b)).

(3) Ejector System, which augments the fan air thrust with an ejector at low speeds and by burning at high speeds (fig. 17(c)).

(4) Tandem Fan System, which splits the fan fore and aft on the fan drive shaft to achieve a variable bypass ratio between subsonic and supersonic operation (fig. 17(d)).

The propulsion system for this vehicle would require high thrust per unit engine weight, volume, and frontal area. Increases in burner and turbine temperatures would be required, and composite and ceramic materials would have to be used extensively throughout the engine. Efficient thrust vectoring would be needed for takeoff and landing as well as for supersonic flight. A lightweight airframe and a fully integrated propulsion/flight control system will be especially important to successful operation of this type of propulsion system.

Hypersonic Vehicles

Renewed interest in hypersonic flight has stemmed from military needs coupled with technological advancements that make hypersonic performance appear achievable. More recently, talk is being heard of a Mach 5 transport capable of carrying 300 to 500 passengers between Washington and Beijing in 3 hr. In the next century, the distinction between aircraft and spacecraft will become less obvious than it is today. It is possible to foresee the development of an "aerospacecraft" that can operate both in the atmosphere and in space. In fact, this capability has recently been proposed as one of the National Aeronautical R&D Goals (ref. 4). Example vehicle concepts to be discussed in this section, as indicated in figure 1, are hypersonic aircraft and transatmospheric vehicles.

Hypersonic aircraft. - Hypersonic aircraft, both manned and unmanned, operating in the sensible atmosphere would have initial capabilities to function at speeds up to Mach numbers of 12. The hypersonic airliner illustrated in figure 18 would make use of multicycle propulsion systems for high total flight envelope efficiency. New materials and structures would allow high heat loads and low weight for both airframe and engine. Cruise Mach numbers of 6 to 8 would be realized with a range of thousands of miles. Integration of the airframe and propulsion system are important for low total vehicle drag and proper conditioning of the intake air for propulsion system operation as well as for the handling of the hot exhaust gases.

Propulsion is one of the key technologies for hypersonic vehicles. Since no single conventional propulsion system can operate efficiently from takeoff to hypersonic flight, either two or more separate engines or combined (hybrid) systems integrating the features of two or more engines are required. Some candidate propulsion concepts include turboramjet, air turboramjet/rocket and hydrogen expansion jet for the lower hypersonic speeds. For very high speeds, up to Mach 12, supersonic combustion ramjets would be utilized. An example of separate engines in a single nacelle is the turboramjet concept shown in figure 19 for a Mach 5 to 6 cruise vehicle. As seen, variable inlet and nozzle geometry would be required to optimally vary the amount of flow to each engine.

Transatmospheric vehicles. - Figure 20 depicts a representative potential transatmospheric vehicle. This vehicle would build on the hypersonic aircraft vehicle and propulsion technologies but with added rocket thrust to achieve orbital speeds. Large payloads are of special interest, as are on-demand

launch, earth return with airplane-like turnaround, and good atmospheric maneuverability. These capabilities would be realized through the application of advanced technology in the areas of propulsion systems, materials and structures, and flight control.

Proposed transatmospheric vehicle systems for the future include concepts with one or two reusable stages. A number of these concepts, some of which are shown in figure 21, were included in the orbit-on-demand vehicle study recently completed by NASA Langley. Currently, only rockets have the capability of providing propulsion over the entire speed range from takeoff to orbit. The ideal propulsion system for this vehicle would allow operation from earth to orbit with a single stage, followed by sustained operation in the earth's atmosphere after reentry. A combined engine system of this type that has been studied is the fan ejector ramjet shown in figure 22, which functions as a fanjet, a ramjet, and a rocket over the range of flight regimes from takeoff to orbit.

Advanced Propulsion Technology

Increased propulsion capability is almost a requirement for initiating development of a new aircraft. This can take the form of a requirement for lower fuel consumption, lower noise, higher thrust-to-weight ratio, and/or longer engine life. Thus, to bring to reality the previously discussed advanced vehicle concepts will require new, more efficient, and more powerful propulsion systems.

Technology areas is which projected advances would have major impacts on propulsion systems of the future have been identified by the "Aeronautics 2000" Workshop propulsion technology panel (ref. 2). Most of these technologies are included in the NASA aeropropulsion key "building-block" discipline areas of internal computational fluid mechanics, structural analysis, materials, and instrumentation and control technologies (fig. 23). In this section, each of the discipline areas will be discussed with inclusion of the technology projections of reference 2. Some highlights of the NASA Lewis aeropropulsion program will be presented to illustrate NASA efforts in these areas.

Internal Computational Fluid Mechanics

Internal computational fluid mechanics (ICFM), as it applies to propulsion, involves understanding and predicting the mass, momentum, and heat transport within engine components (e.g., inlets, compressors, combustors, turbines, and exhaust nozzles). An effective program requires a balanced approach between analytical and experimental research. Key ICFM analytical activities include physical modeling, algorithms, numerics, mesh construction, code efficiency, and graphics. Experimental activities are directed at understanding complex flow phenomena and verifying the new computational methods.

Internal computational fluid mechanics represents a major opportunity in propulsion to improve productivity in the design/development process. As indicated in figure 24, the cost of developing a new engine including product improvement is nearly two billion dollars. A significant part of this cost can be attributed to failure of the fluid mechanics and structural design

systems to meet design intent. The generation of efficient ICFM, as well as structural, design tools and methodologies would have a major impact on both cost and time of development of future propulsion systems.

The state of current internal-aerodynamics design practice varies with the type of component. For turbomachines, the prevalent design method is the pseudo-three-dimensional technique wherein inviscid flow calculations are performed on intersecting two-dimensional surfaces within the blade passage. Viscous effects are included by boundary-layer computations on blade surfaces and endwalls. Twoand three-dimensional viscous methods for turbomachines are currently being developed and tested.

For inlets and nozzles, current design practice is more advanced. Three-dimensional viscous marching analyses are being used for both supersonic and subsonic inlets. An approximate form of the Navier-Stokes equations is solved and the numerical solution proceeds from plane to plane through the length of the duct. One inlet analyzed by this method had a curved centerline and a cross section that varies from rectangular at the entrance to circular at the exit (compressor face). The duct geometry and computed exit total-pressure distortion are shown in figure 25.

Improvements in current analysis capabilities will require a better understanding of complex internal flow phenomena. For example, the complex internal flow of the centrifugal compressor is not well understood. A 5-ft diameter low-speed compressor (fig. 26) is currently being fabricated at NASA Lewis to provide experimental data for developing detailed flow models and for verifying advanced computer codes. The compressor will be heavily instrumented and will have provision for flow visualization and laser doppler velocimetry.

At the present pace of evolution of computational algorithms and development of computational power, there almost surely will be a capability, by the year 2000, to compute the three-dimensional viscous flow in fans, compressors, and turbines with sufficient dispatch to make the process useful in design. This would permit quantitative design trade-offs in which the aerodynamic performance is balanced against weight, structural characteristics, and perhaps even cost. Computational fluid mechanics advancements also will benefit the area of flows with chemical reactions such as within a combustor. By the year 2000, a steady-state calculation with chemical reaction and with a turbulence model that can predict reasonably the mixing in three-dimensional swirling flow fields is a distinct possibility.

Structural Analysis

The major problems in structural dynamics of aircraft propulsion systems center on an inability to predict accurately the vibration frequencies, patterns, and amplitudes of turbine engine and turboprop blading and the vibration behavior of the entire engine as an interacting dynamic system. Sustained vibration and large transient forces and deflections in propulsion system blading and in larger components such as shafts or casing parts can lead to fatigue failures and consequent loss of performance or of overall structural integrity (fig. 27).

Conditions that lead to sustained vibration or large transients must either be predicted in the design phase and avoided, or found and corrected in

the development phase. Avoiding the high cost of fixing vibration and transient problems in the development phase, which accounts for a significant part of the development cost previously shown in figure 24, is a major motivation for trying to improve prediction capabilities. Further development of computer codes is, therefore, needed to predict the deformations due to incidents such as blade loss and hard landings so that blade tip rubs, gas-path-seal wear, and damaging bearing loads can be avoided by appropriate design. One such computer code was recently developed by NASA Lewis for analyzing transient vibrations of entire turbine engines. This code, called TETRA (Turbine Engine Transient Response Analysis), was developed to analyze the transient response to events such as blade loss but can also be used to explore the effects of manufacturing imbalance.

Fans and turboprops are subject to flutter that is induced by a steady airstream above some velocity. To predict the airspeed at which flutter ensues in order to ensure that the onset speed lies outside the flight envelope is a major aeroelasticity problem. More accurate flutter analyses would permit the use of blade shapes that would give higher performance and lower noise. Also, these analyses would provide the means for evaluating schemes for delaying the onset of flutter.

Considerable progress is being made in the area of flutter analysis. The first studies of the effect of sweep on fan blade flutter were made by applying the analytical methods developed for aeroelastic analysis of advanced turboprops. It was found that a small amount of sweep (15°) was beneficial for increasing flutter onset speed, but that a larger sweep (30°) was detrimental. Experimental results were in good qualitative agreement. To improve the understanding of blade mistuning effects, a new analytical model was used to quantify the effects of frequency mistuning on the flutter boundaries of an advanced fan. The results, shown in figure 28, indicate that a moderate amount of intentional mistuning has the potential to alleviate flutter problems in unshrouded high aspect-ratio fans.

By the year 2000, blade frequency analysis is expected to be accurate to better than 5 percent, taking into account all major types of modes including plate and shell modes and disk and shaft coupled modes; hence, it should be possible to design blading to avoid excessive resonant response to periodic flow variations. It also may be possible to accurately predict overall engine response to transient events such as blade loss, hard landings, and sharp maneuvers. By intentional introduction of blade "mistuning" and of damping materials and mechanisms, flutter speeds of fans, compressors, and advanced turboprops can be expected to increase by at least 10 percent. Forced vibration levels can be reduced by 50 percent by such methods. It should not only be possible to predict flutter and forced response of turboprops, but also the interactions of such props with nacelles, pylons, and wings.

Materials

Engine materials have paced the progress of propulsion from the inception of the turbine engine and will continue to do so for the foreseeable future. This has occurred primarily as a result of the ever increasing temperature capability, as seen in figure 29, provided by new material developments. Two major thrusts in engine materials are foreseen in the next few decades: the progressive substitution of ceramics for metals in the hot section and the introduction of nonmetallic composites for lightweight structures.

Hot-section materials. - The evolution of hot-section materials will proceed in three areas: the continued development of metallics, especially anisotropic superalloys; thin layers of ceramics as a thermal barrier; and solid ceramics. Continued progress in superalloys is likely to yield an improvement of 200 °F in allowable metal temperature before fundamental melting point limitations are reached. Ceramics presently are being used in burner liners and vane platforms as a thermal barrier. The thermal barriers are being used to gain extra durability; however, they also have a tendency to spall, and this has prevented more widespread use. The next decade will see the further use of thermal barrier coatings as a "prime reliable" part of the airfoil. Solid ceramic structures appear only in research engines at this time.

The three main technical thrusts needed to create the technology base to improve ceramic material reliability/reproducibility are: materials and processing, design methodology, and life prediction. The overall objectives of these major thrusts are to understand the relationships between materials, processing, microstructure, and properties, and to apply this understanding to improve design tools for brittle materials and to improve the capability for accurately predicting the lives of ceramic components.

At NASA Lewis, the ceramics work is focused on increasing material strength and on increasing reliability without sacrificing strength. A recently developed silicon nitride-zyttrite (yttria stabilized zirconia) composition has about the same room temperature strength and nearly double the high temperature strength as compared to a commercial silicon nitride material. In the area of materials processing, it was found that a new sintering process using high nitrogen pressure results in improved high-temperature (2500 °F) strength as compared to a commercially sintered silicon nitride. Continued improvement in the strength of ceramic materials will pave the way for the use of solid ceramic structures such as the silicon nitride turbine vane shown in figure 30.

Reliability assurance requires the availability of nondestructive evaluation techniques not only for defect detection, but also for verification of physical and mechanical properties. The strength of structural ceramics can generally be expected to vary as a function of density. A recent investigation showed that ultrasonic velocity can be used as a measure of bulk density for sintered silicon carbide. The technique is simple, inexpensive, and accurate, and it could be used to assure the reliability of components such as the silicon carbide turbine rotor shown in figure 31. This ceramic rotor and the previously shown ceramic stator were fabricated and tested under NASA Lewis programs sponsored by the U.S. Department of Energy.

Advances in high-temperature materials by the year 2000 offer the possibility of materials able to withstand temperatures 400 to 600 °F higher than today's materials. The turbine blade materials in this time period most likely will be advanced versions of the present single crystal-type systems with increased dependence on thermal barrier coatings to reduce cooling requirements. However, it is highly likely that combustors and turbine vanes will be made of ceramic or ceramic/composite structures. This application, then, would be the first to take advantage of the brittle high-temperature materials. The mechanisms of thermal barrier coating degradation and failure are expected to be understood so that ceramic coating systems can be exploited fully.

Nonmetallic composites. - Composite structures are an integral part of engine and propulsion system improvement as they are lighter in weight and more cost-effective than corresponding metal components. In order to maintain this propulsion system trend, increased composites usage in the engine will be required. The extended use of composites in today's engines is limited by the operating temperature limits of the available composite system. Development of current composite systems has allowed the fabrication of engine parts for operation up to 550 °F at reduced weight and cost. Usage of composites in major engine structures can be expanded vastly if higher temperature capability can be achieved.

The key issues to be addressed for an advanced higher-temperature composite include the identification of a polymer and fiber system with adequate oxidation stability, material properties, and polymer processing capability. The achievement of capabilities for both life prediction and condition monitoring are also important. NASA Lewis is conducting programs addressing these key issues. For the polyimide PMR-15, a method was found to provide a reduction in cure temperature from 600 to 500 °F without sacrificing thermo-oxidative stability and mechanical property retention. In the area of condition monitoring, the results of a recent study showed that ultrasonic attenuation measurements can be used to indicate the onset of serious fatigue damage since both flexural stiffness and ultrasonic attenuation correlate in the same manner with number of fatigue cycles.

Continued progress in these areas has allowed extension of the composite material application technologies shown in figure 32. This photo shows a NASA research engine with a graphite/PMR-15 inner cowl and a graphite/epoxy fan frame. The graphite/PMR-15 composite is now being used for engine structural members such as outer casings.

The probability of developing and implementing a suitable composite system for temperatures approaching 1000 °F by the year 2000 appears possible, assuming a comprehensive effort including multiple independent approaches of the major issues is undertaken. If this polymer program developed an 800 to 900 °F capability only, it would still go a long way toward providing composites for future engine systems.

Instrumentation and Controls

The understanding and control of the physical processes in aircraft gas turbines has been greatly constrained by the limited ability to make direct measurements in the real environment. In an operational engine, one must often measure not the physical quantity of interest, but one within the capability of the sensor technology followed by quasi-empirical modeling to infer the desired variables. In spite of these limitations, the control complexity of aircraft turbine engines has been increasing, as seen in figure 33, and will continue to do so.

Instrumentation. - Instrumentation technology requirements are driven by both research and operational needs. In research, the need is to explore in detail the physical processes inside an engine environment in order to understand the fundamental phenomena as well as to verify newly developed analytic tools. For production engines, very high sensor reliability is of paramount concern and is an important constraint on the development of improved sensor capability for engine control, diagnostics, and performance retention.

Most of the research instrumentation systems of the future will be based on optics with heavy emphasis on the melding of the properties of lasers and microcomputers. In the field of anemometry, the fringe laser system is being combined with the recently developed direct doppler system to enable the measurement of all three components of velocity under circumstances of extremely limited access, as is normally encountered in a turbine engine. Modern lasers coupled with a special motion picture camera are being used to obtain holographic motion pictures, which are enabling revealing looks at the flow phenomena in rotating machinery. A new schlieren photography technique, called color rainbow schlieren, enables quantitative information to be obtained from the colors of the image on the resulting color photographs. A rainbow schlieren photo of flow around a supersonic inlet is shown in figure 34.

A research area in instrumentation that does not involve optics is that of thermocouples for measuring the temperature of various internal engine parts. A process has been developed for the direct application of thin film thermocouples to the blade and vane surfaces using sputtering technology (fig. 35). The sensor installation is a few hundred micrometers thick and, thus, significantly alters neither the structural properties of the blade nor the aerodynamic flow around it.

Specific target areas for new and improved instrumentation techniques include: flows near surfaces (airfoils and end walls); rotating frame measurements of flow and stress; hot section measurements (metal and flow temperature, stress, heat flux, etc.); in situ structural assessment (flaw detection, creep, etc.); and improvement in sensor life and reliability. By the year 2000, sensor technology is expected to have advanced to the point where: (1) comprehensive hot section measurements can be done routinely during development; (2) operational engines will contain large numbers of high-reliability sensors; and (3) in situ structural assessment will have become widely used.

<u>Controls</u>. - Key future activities involve the use of real-time intelligence to improve propulsion system performance and operability by closed-loop control. Some areas where this technology can have a significant impact include compressor stall alleviation, active clearance control, secondary airflow modulation, and active pattern factor control based on blade stresses or temperatures. In order to achieve the potential benefits, improved sensor/computer/effectuator systems and improved component models must be developed.

NASA Lewis is currently developing the first step in this advanced controls effort, the advanced sensor failure detection, isolation, and accommodation (ADIA) program. The ADIA algorithm incorporates real-time decision-making logic to detect sensor failures in propulsion control systems to improve overall system reliability and operability. An evaluation has demonstrated the ability of the algorithm to completely cover large abrupt sensor failures and most small drift failures.

By the year 2000, there is the possibility that active stall alleviation and pattern factor control will have been demonstrated on the test stand. The continuing microelectronic revolution implies that the onboard computational capacity (both processing and storage) will increase by orders of magnitude over current systems. This increase in capability can be employed to improve greatly the traditional engine fuel control. Also, it will be used to alter

fundamentally the nature of gas turbine components and subsystems from open to closed-loop operation resulting in more optimal performance.

CONCLUDING REMARKS

We have seen that there are still many great strides to be made in aeronautics, and that propulsion is an essential, if not the most essential, ingredient. Propulsion technology projections recently made for the year 2000 provide guidance for aeropropulsion research at NASA. Design capabilities are expected to include three-dimensional viscous flow analysis for all components. Advanced hot-section materials could provide 400 to 600 °F higher temperature capability due primarily to the increased use of ceramics. Lightweight composite materials may be in use for temperatures approaching 1000 °F. Improved structural analysis capability should result in at least a 10 percent increase in blade flutter speed boundary and a 50 percent reduction in engine vibration level. Sensor technology improvements can provide routine comprehensive hot-section measurements and in situ structural assessment. Advancements in control technology will eventually permit active stall alleviation and pattern factor control.

Integration of these propulsion technologies with all other aeronautics technologies will provide the basis for twenty-first century vehicles, many types of which do not now exist. We can foresee subsonic commuter and transport aircraft that consume only half the fuel as do today's jetliners; vehicles that takeoff and/or land vertically and fly at high subsonic or supersonic speeds; airliners that fly at sustained supersonic and, possibly, hypersonic speeds; and transatmospheric vehicles that provide a reusable on-demand launch to orbit capability with high maneuverability in the atmosphere. The twenty-first century will certainly be a most exciting time for aeronautics.

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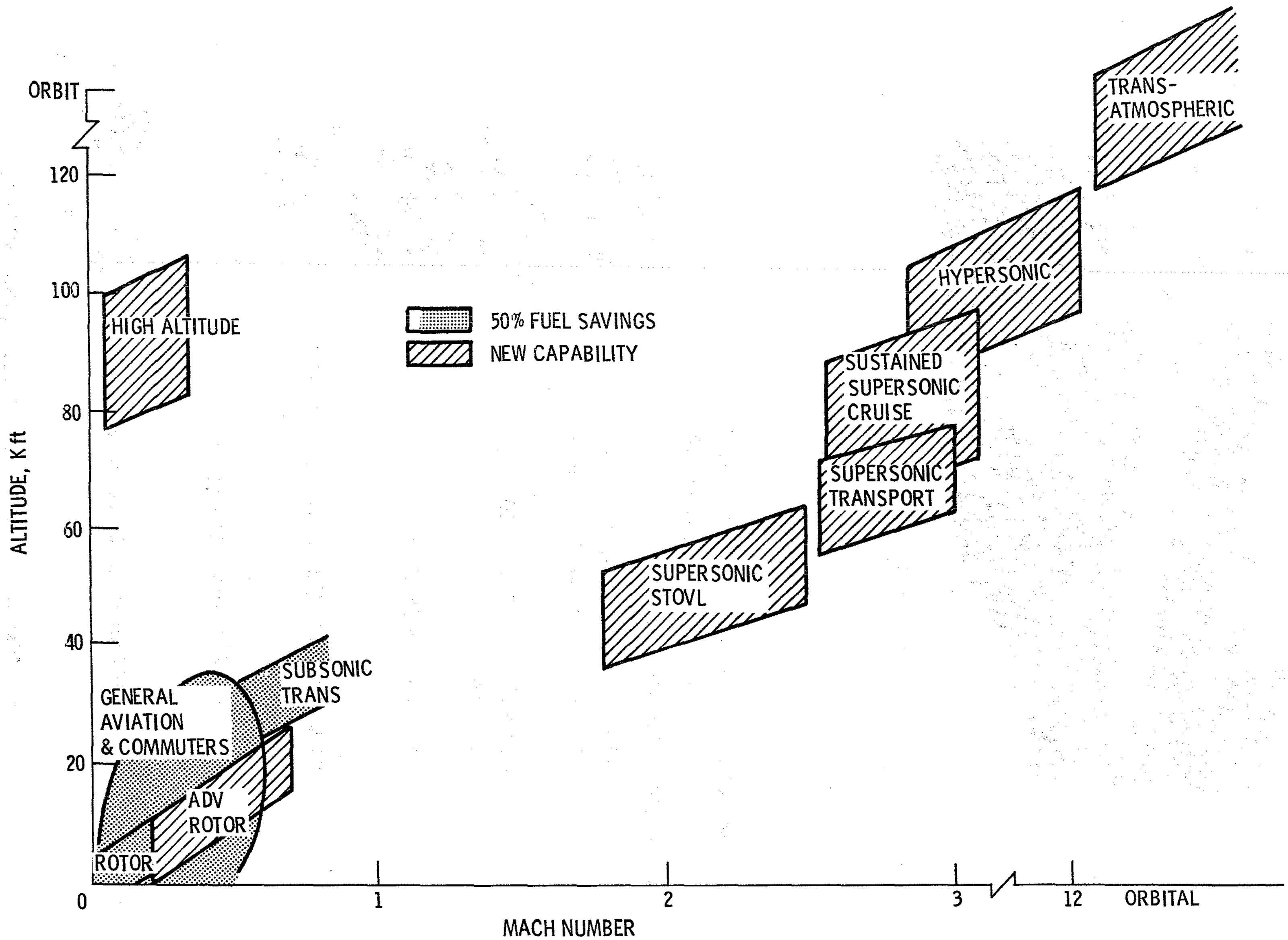


Figure 1. - "Aeronautics 2000" advanced vehicle concepts.

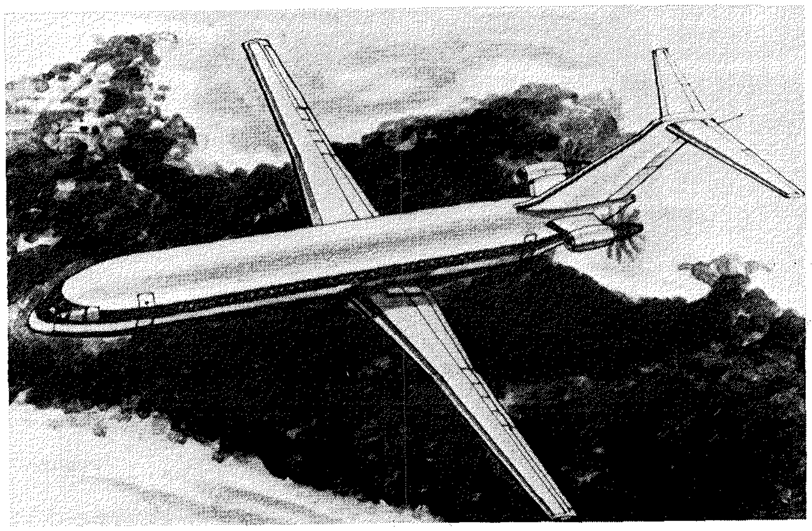


Figure 2. - Subsonic civil transport.

OBJECTIVE ESTABLISH TURBOPROP TECHNOLOGY FOR MACH 0.65-0.85 APPLICATIONS

PROGRAM GOALS/BENEFITS

15-30% FUEL SAVINGS OVER TURBOFANS WITH COMPARABLE CORE TECHNOLOGY

7-15% DOC SAVINGS OVER COMPARABLE TURBOFANS

SAFE AND RELIABLE SYSTEM

CABIN NOISE/VIBRATION SIMILAR TO TURBOFAN'S

MEET FAR 36-III COMMUNITY NOISE REGS

TECHNOLOGY READINESS BY LATE 1980'S

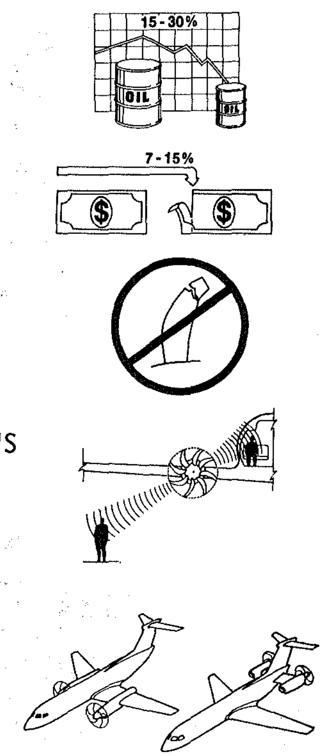
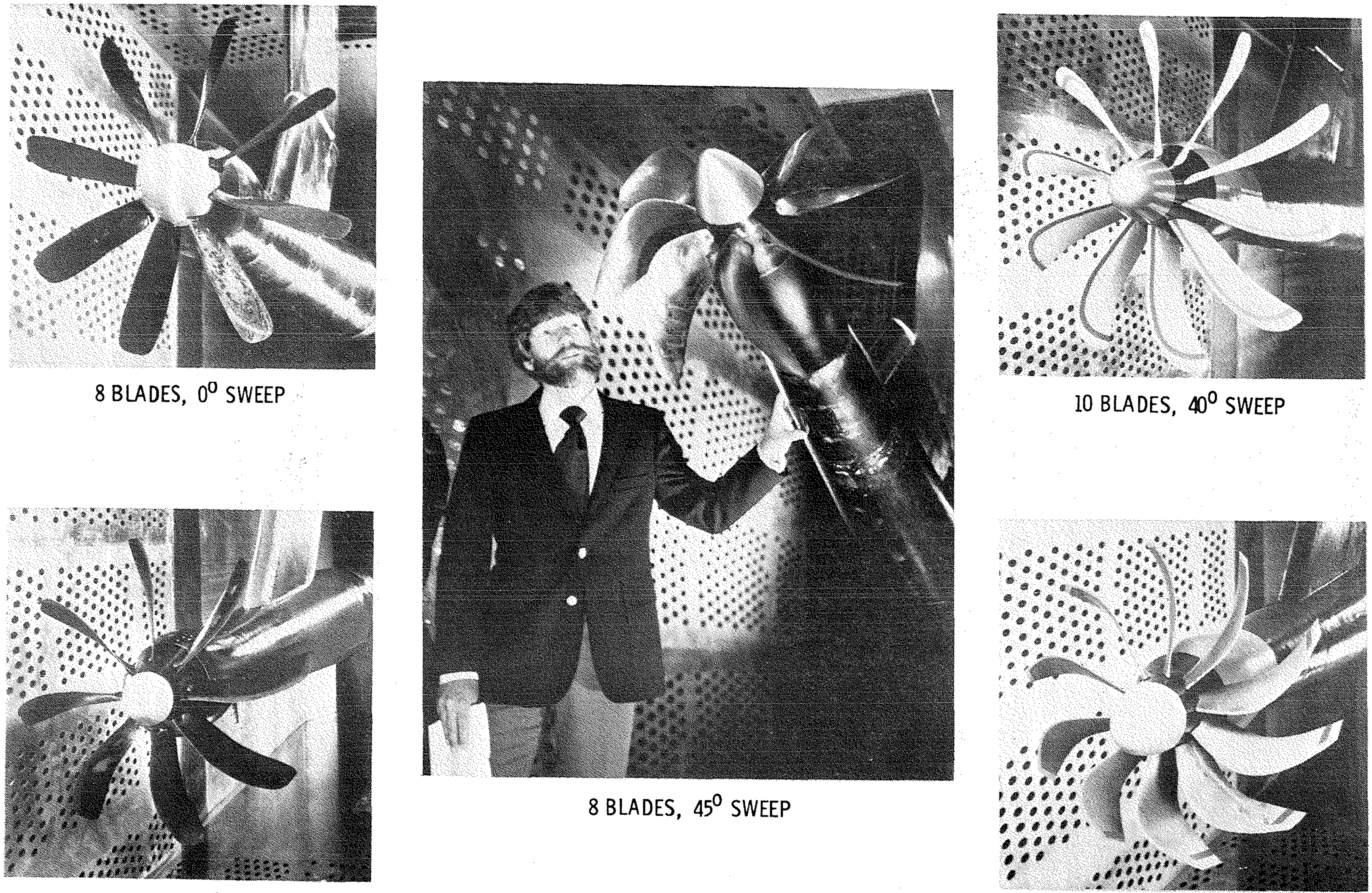


Figure 3. - Advanced Turboprop Program objective, goals and benefits.



8 BLADES, 0° SWEEP

8 BLADES, 30° SWEEP

8 BLADES, 45° SWEEP

10 BLADES, 40° SWEEP

10 BLADES, 60° SWEEP

Figure 4. - Propeller models installed in wind tunnel.

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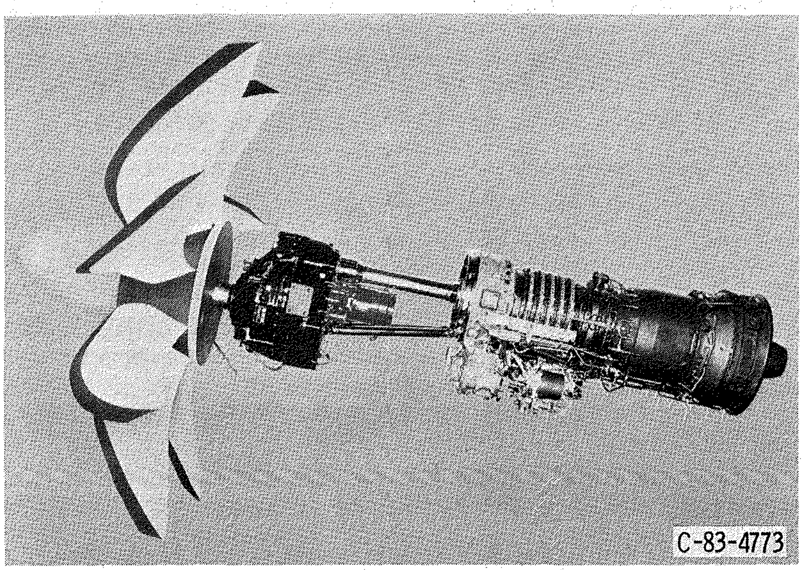


Figure 5. - Single-rotation turboprop system mock-up.

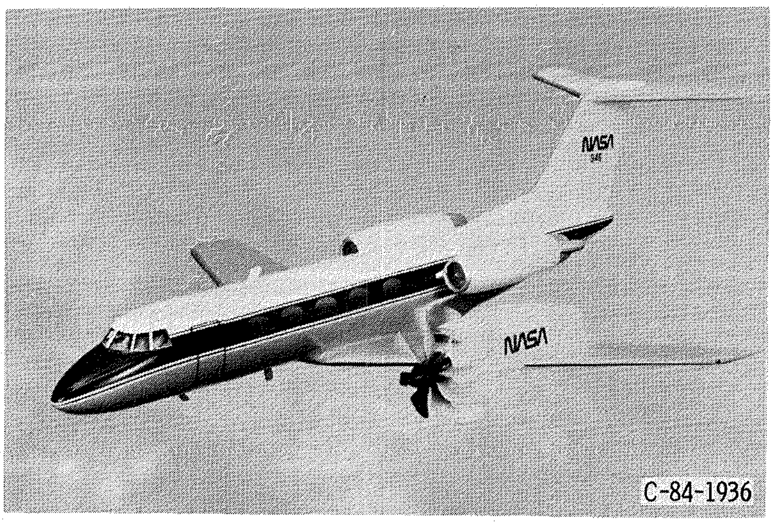


Figure 6. - Gulfstream II with turboprop mounted on wing.

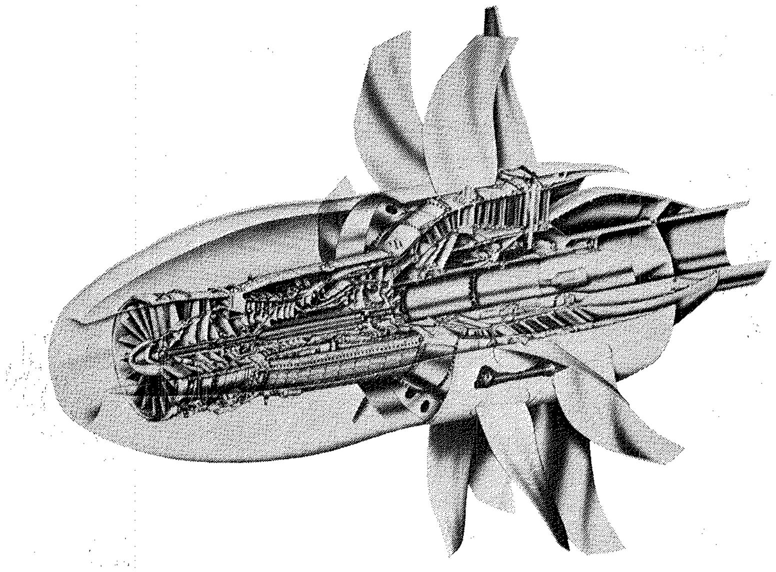


Figure 7. - Unducted fan engine (UDF).

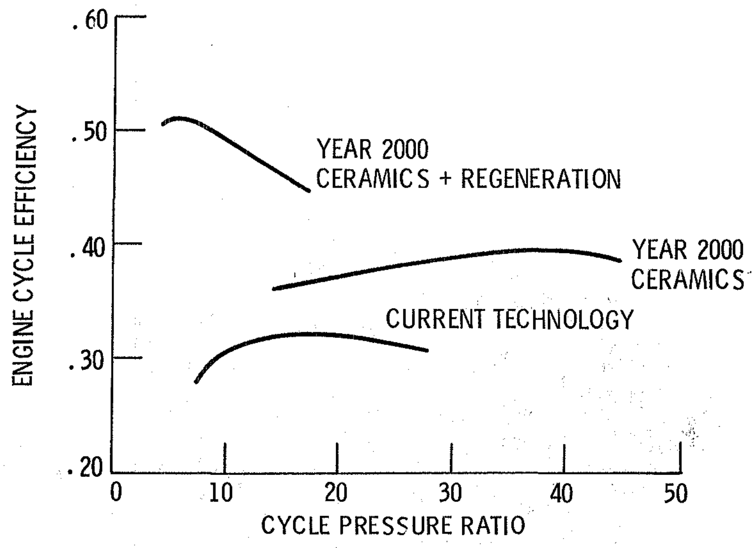


Figure 8. - Small engine efficiency improvement potential.

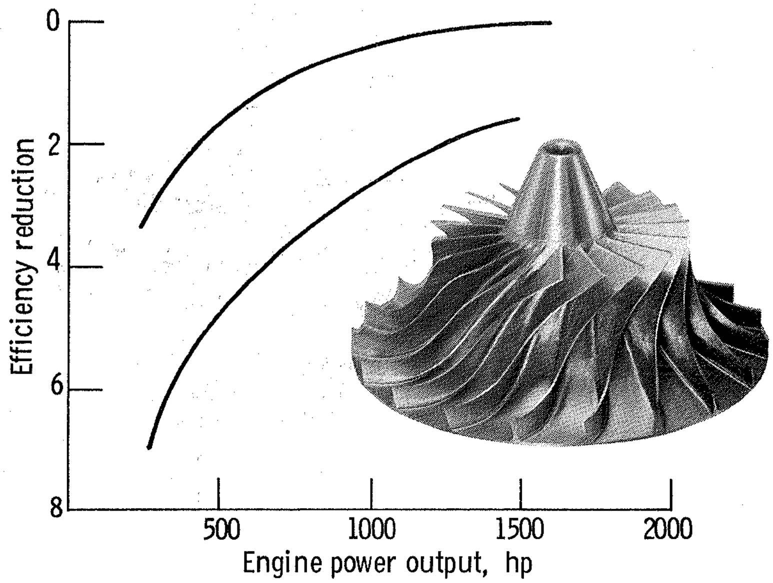


Figure 9. - Compressor efficiency size penalty, current and advanced.

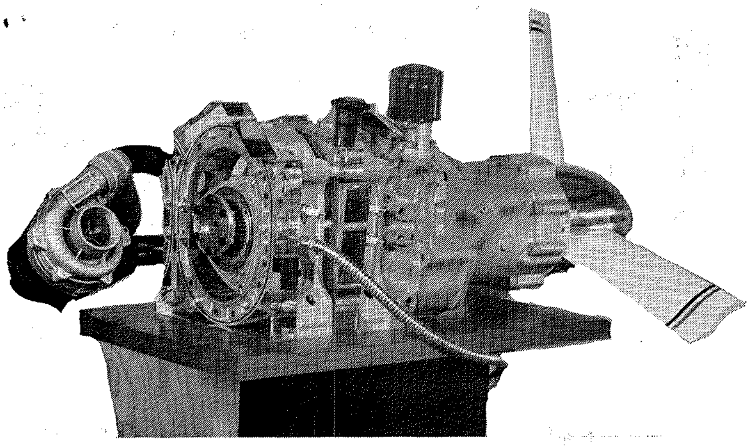


Figure 10. - Aircraft rotary engine concept.

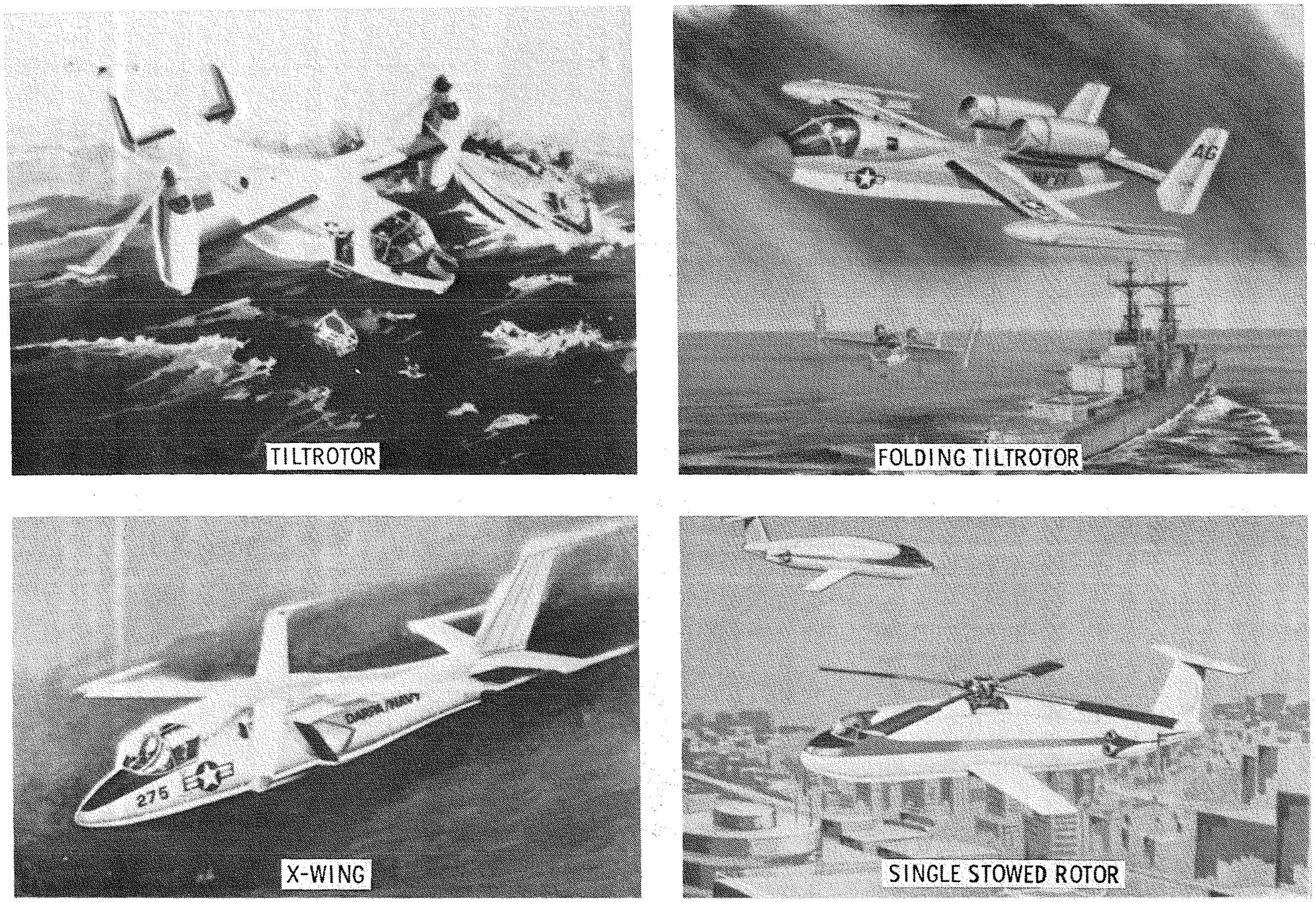


Figure 11. - High-speed rotorcraft concepts.

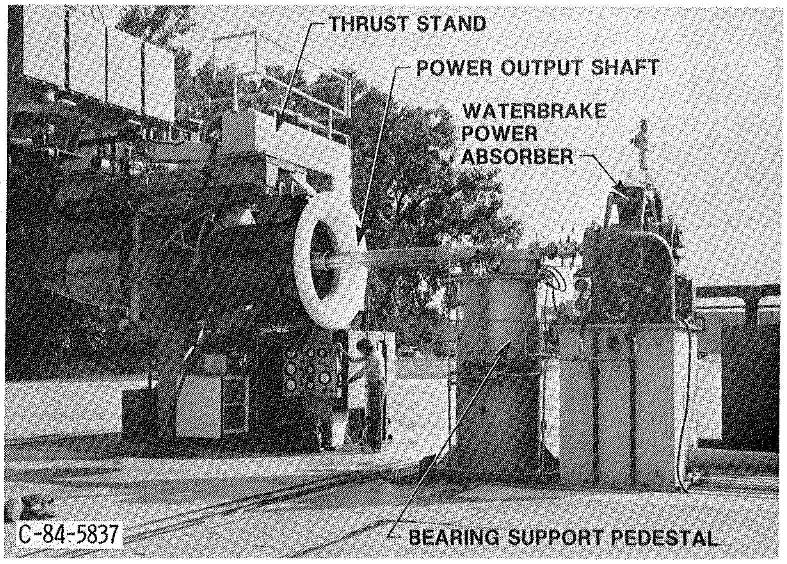


Figure 12. - TF34 "convertible" engine test.

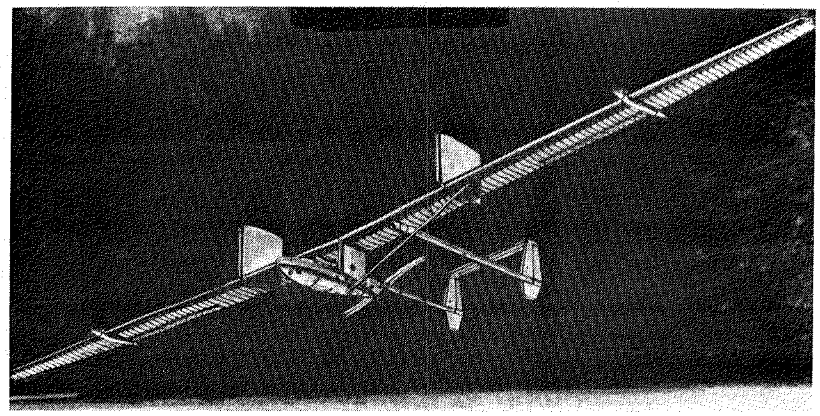


Figure 13. - Extremely high altitude solar-powered aircraft.

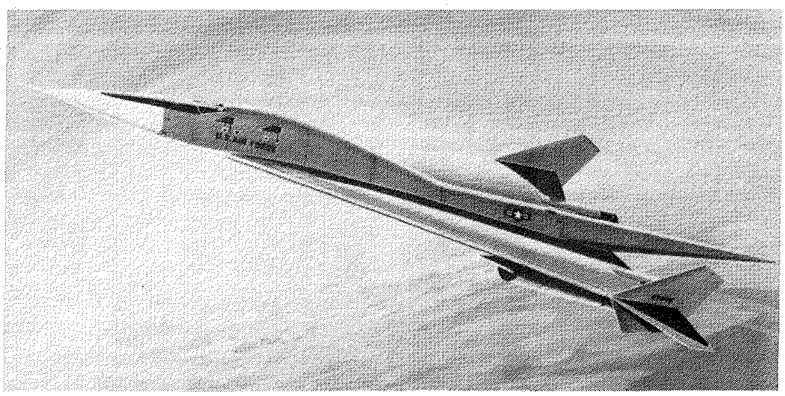


Figure 14. - Sustained supersonic cruiser.

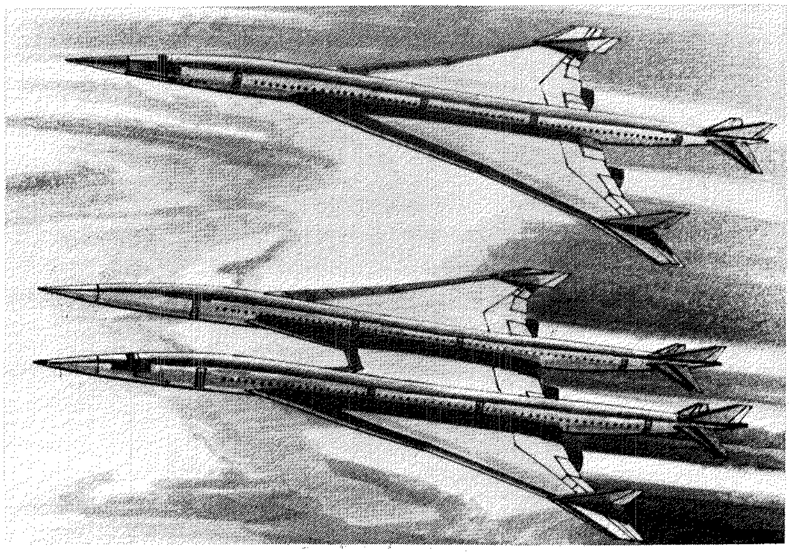


Figure 15. - Supersonic transport concepts.

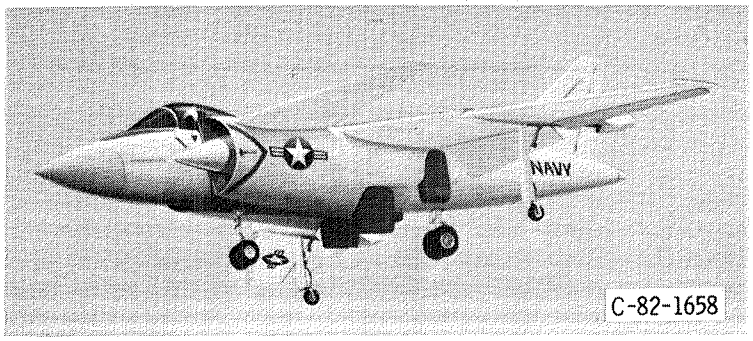
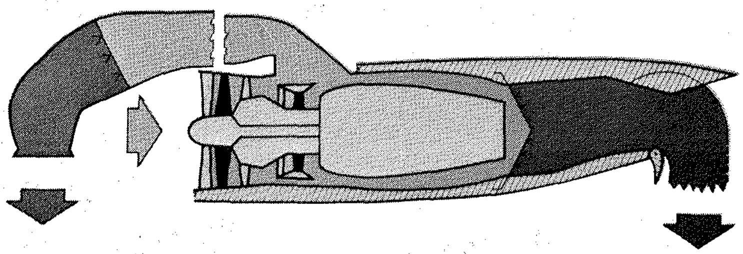
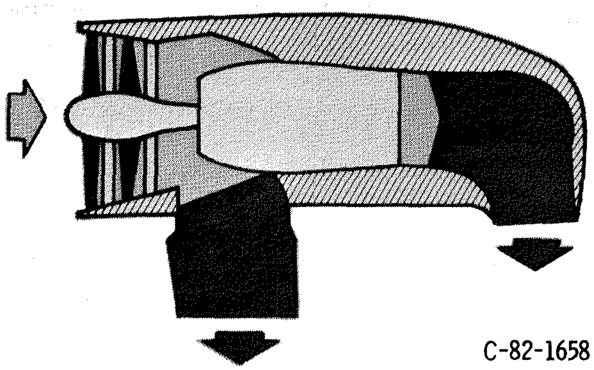


Figure 16. - Supersonic short takeoff-vertical landing (STOVL) aircraft.

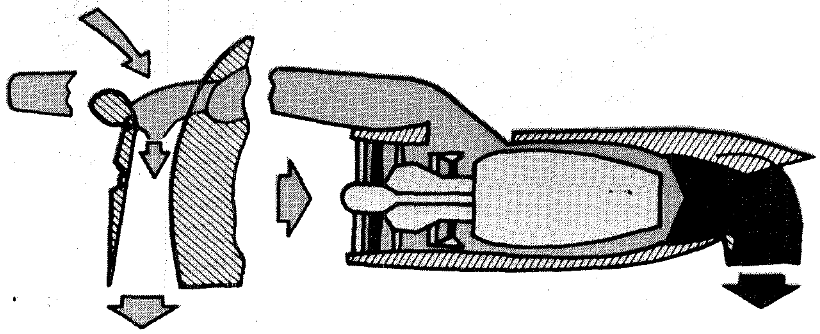


(a) Remote augmented lift system.

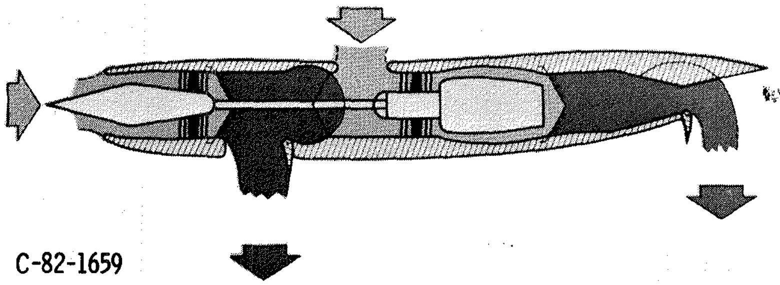


(b) Deflected thrust system.

Figure 17. - Supersonic STOVL propulsion concepts.



(c) Ejector system.



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(d) Tandem fan system.

Figure 17. - Concluded.

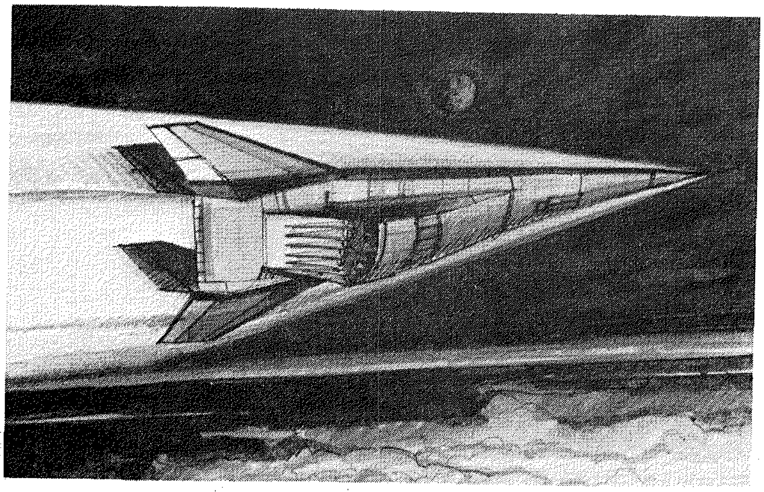

Figure 18. - Hypersonic airliner.

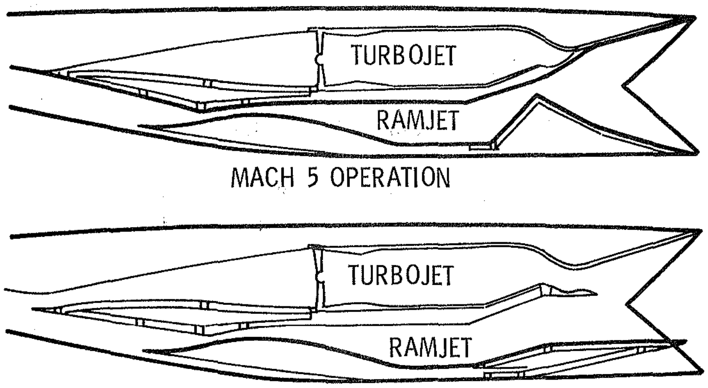

Figure 19. - Turboramjet concept showing required inlet and nozzle variations.

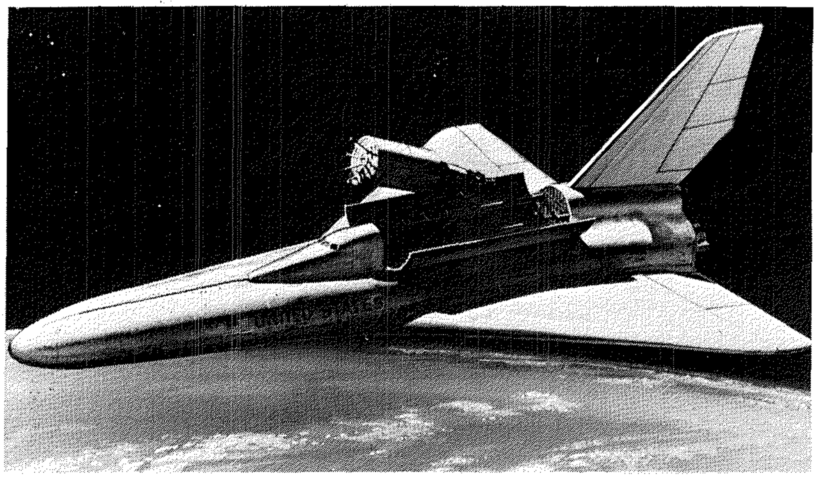

Figure 20. - Transatmospheric vehicle.

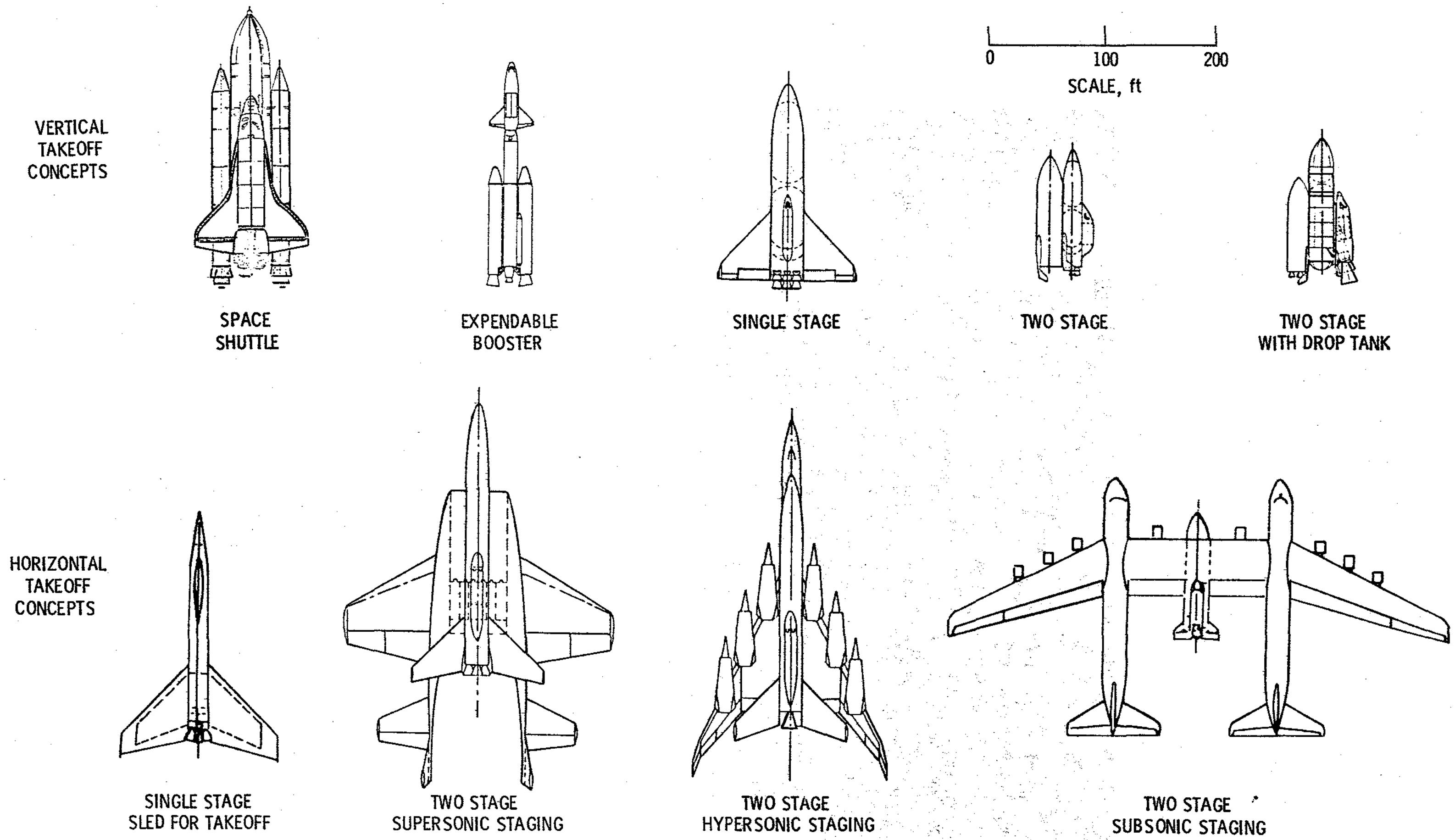

Figure 21. - Orbit-on-demand vehicle concepts.

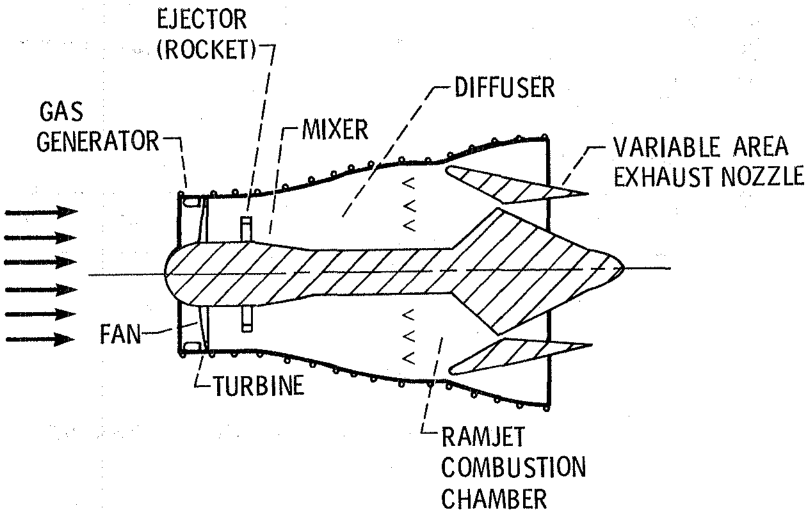

Figure 22. - Fan ejector ramjet.

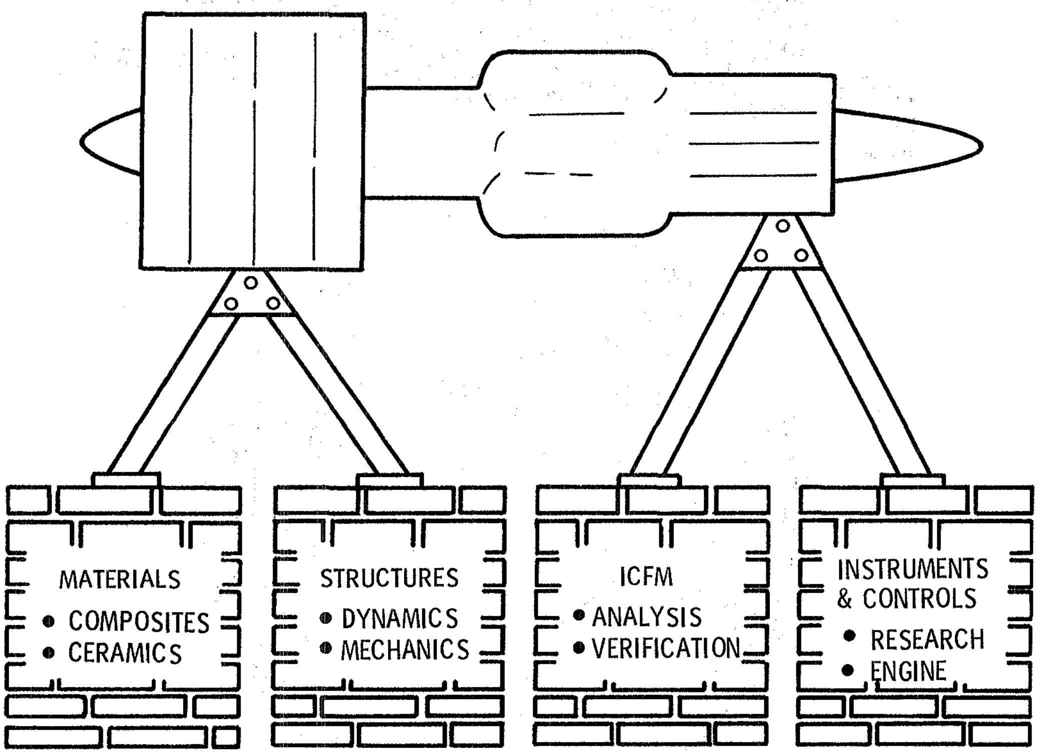

Figure 23. - Foundation for future propulsion opportunities.

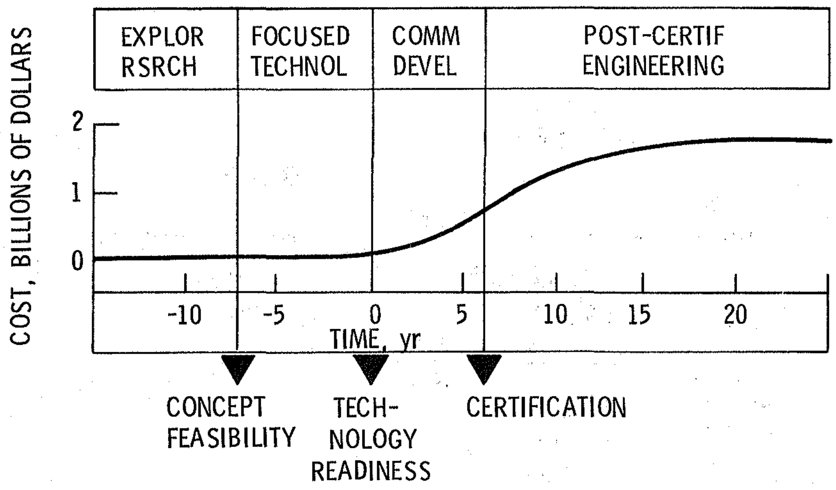

Figure 24. - Engine development/improvement cost.

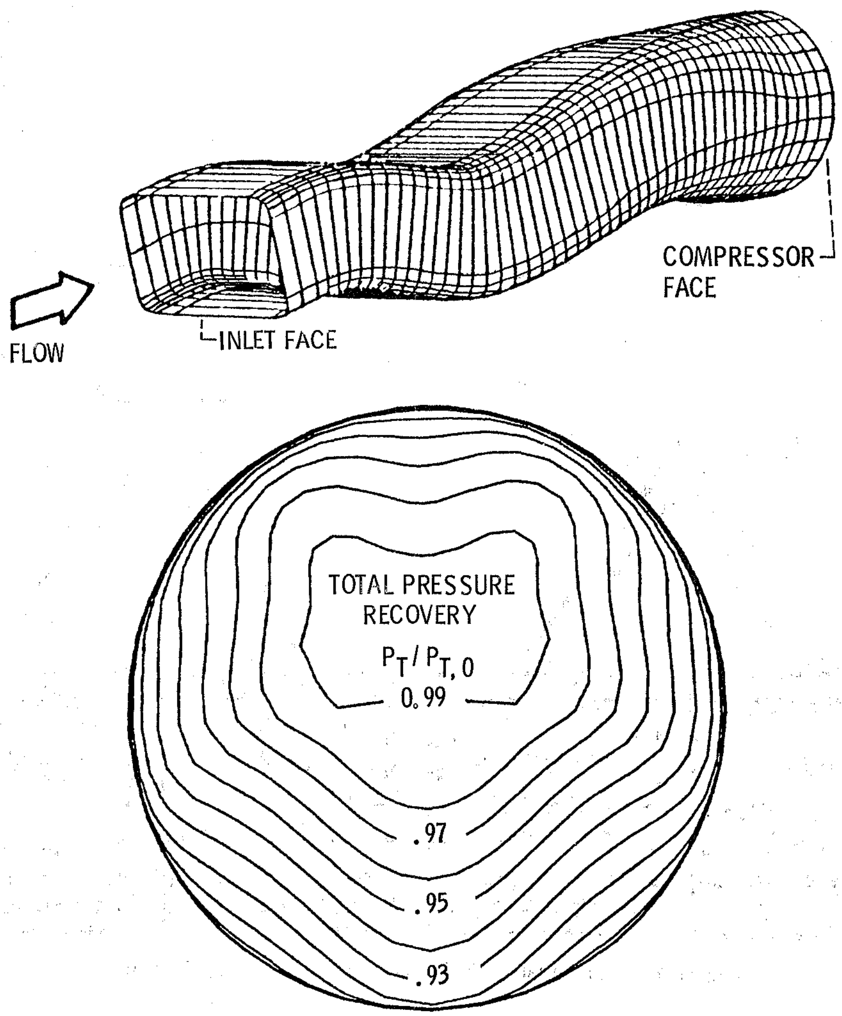

Figure 25. - Computed total pressure recovery for engine inlet duct.

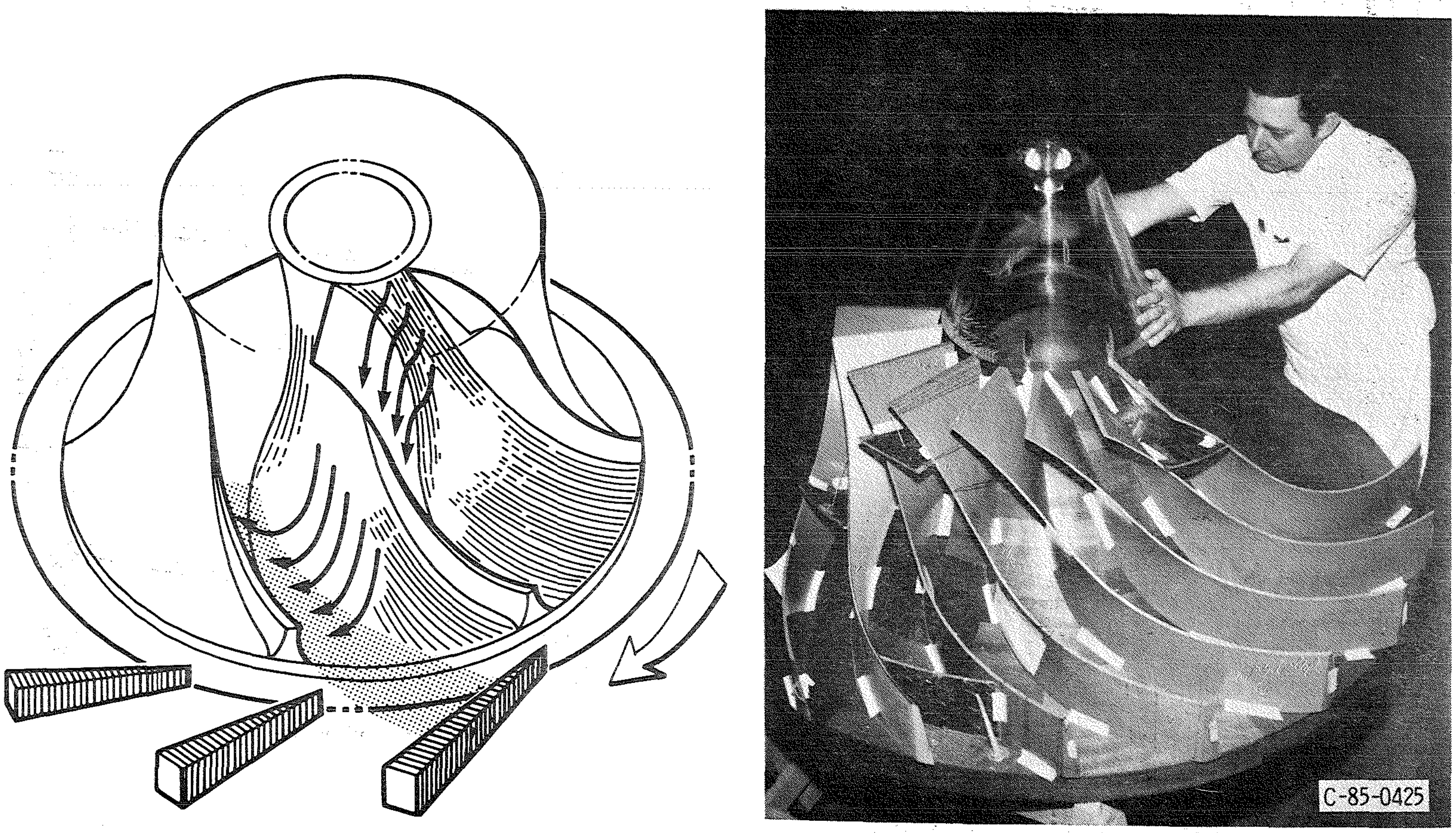

Figure 26. - Large low speed centrifugal compressor for benchmark experiments.

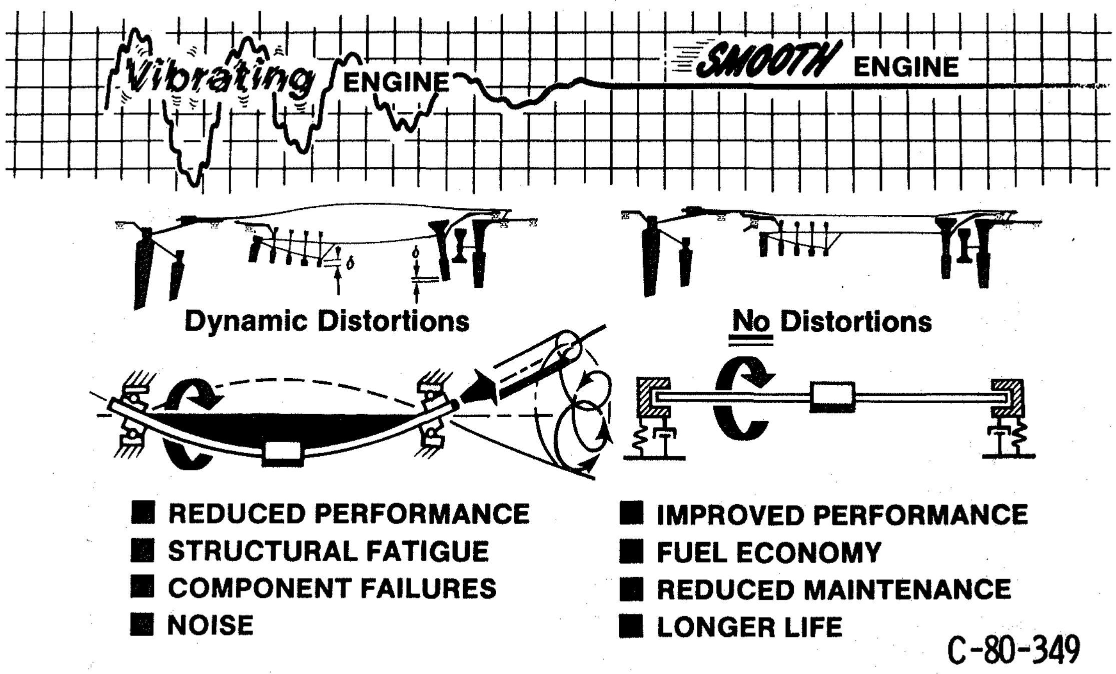

Figure 27. - Rotor dynamics effects.

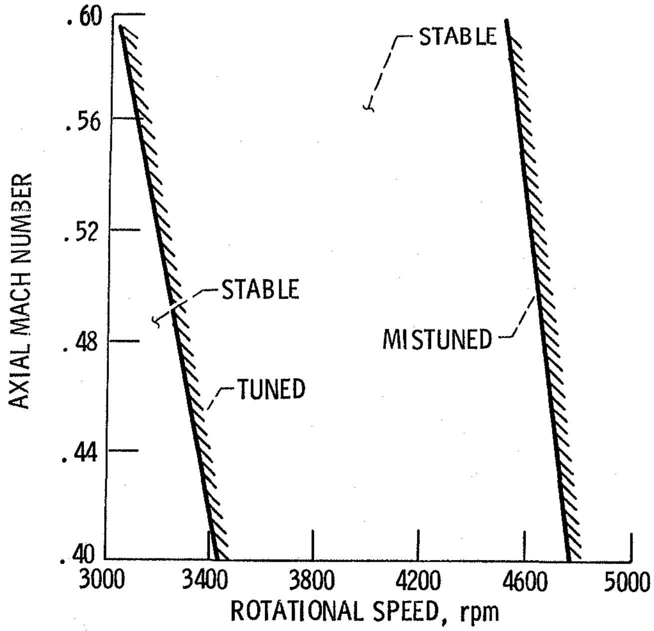

Figure 28. - Flutter boundaries with mistuning.

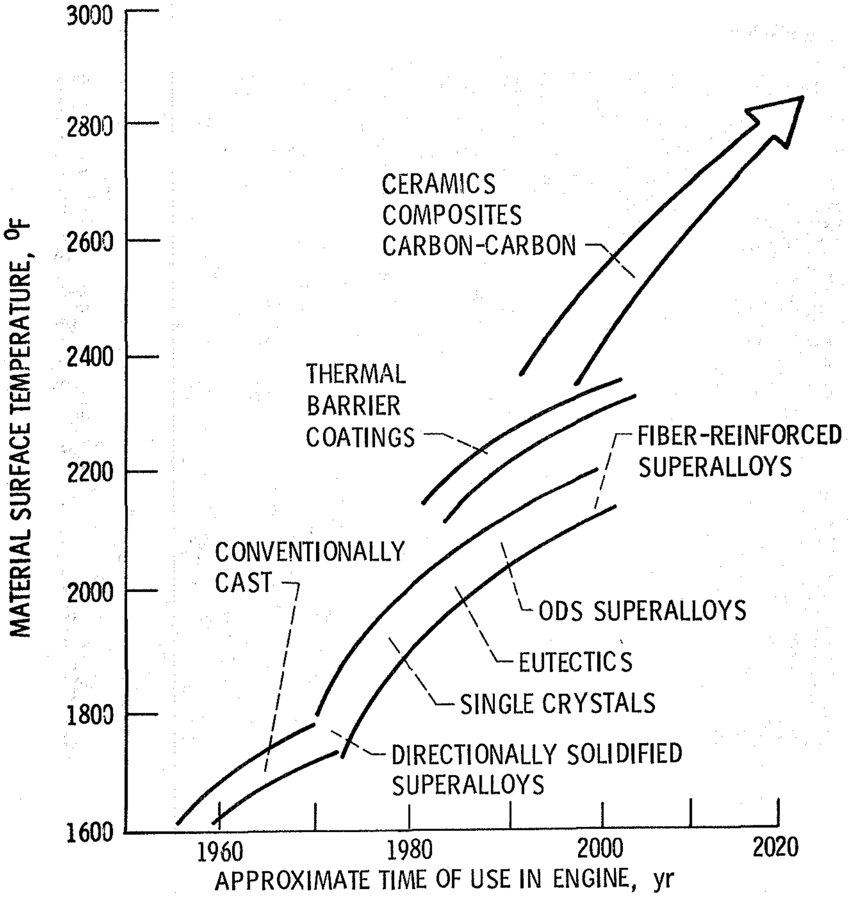

Figure 29. - Turbine engine hot-section material trends.

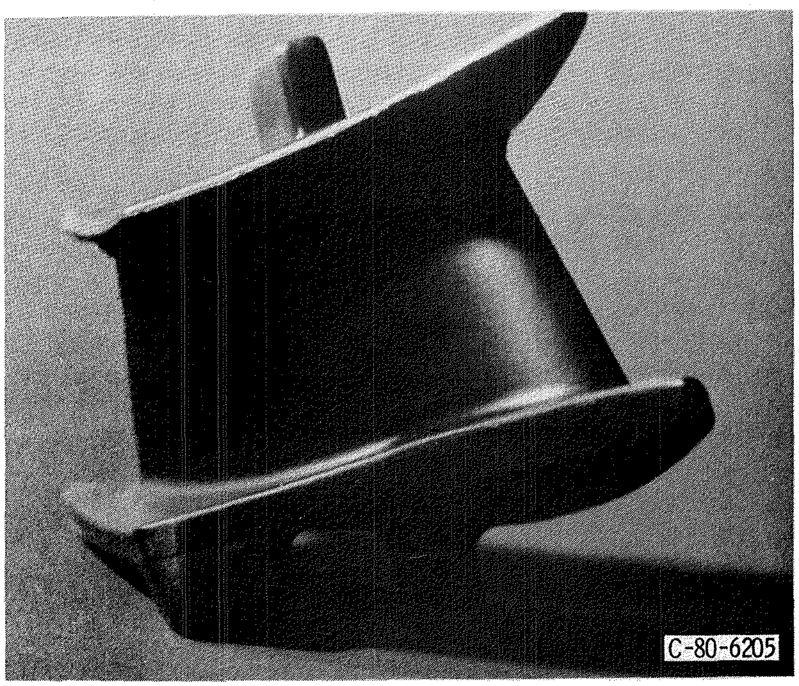

Figure 30. - Silicon nitride ceramic turbine vane.

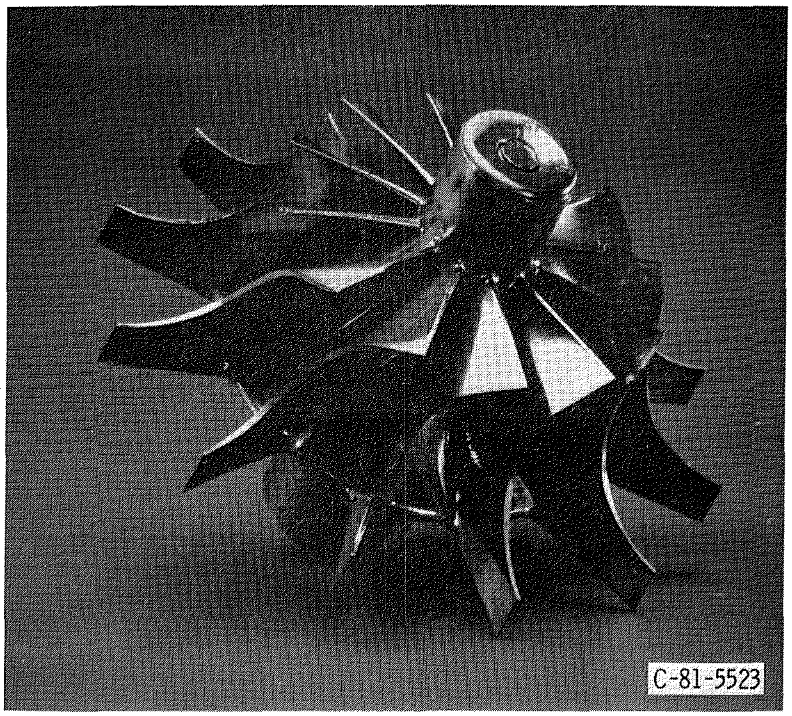

Figure 31. - Silicon carbide ceramic radial-turbine rotor.

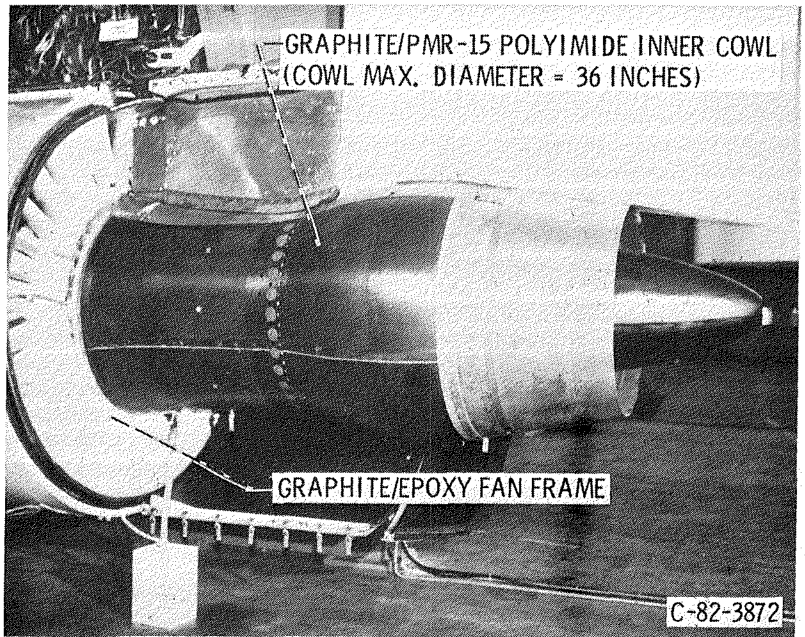

Figure 32. - NASA research engine with composite components.

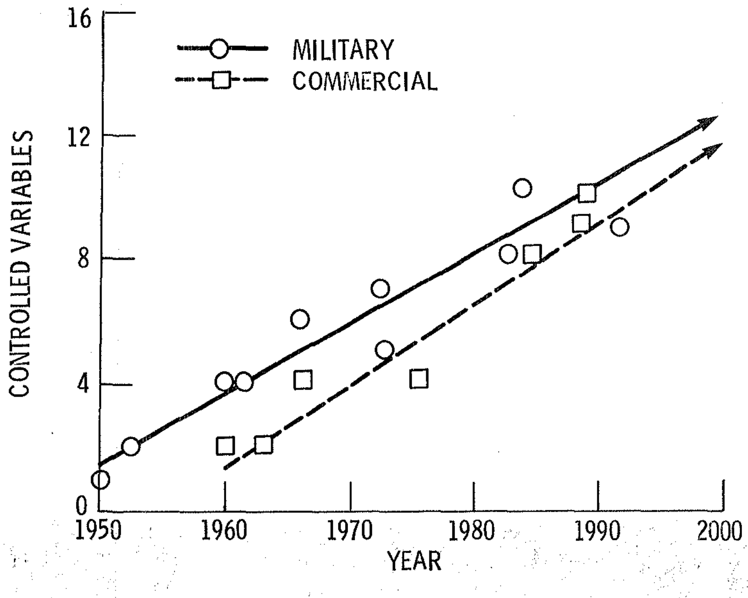

Figure 33. - Trends in control complexity of aircraft turbine engines.

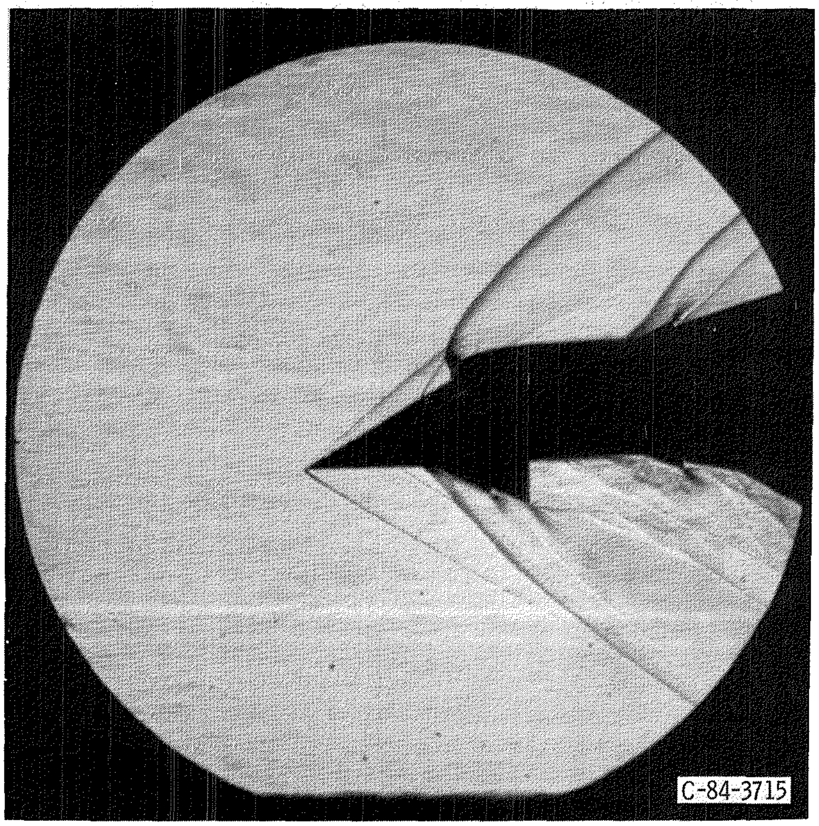

Figure 34. - Schlieren photo of flow around a surpersonic inlet.

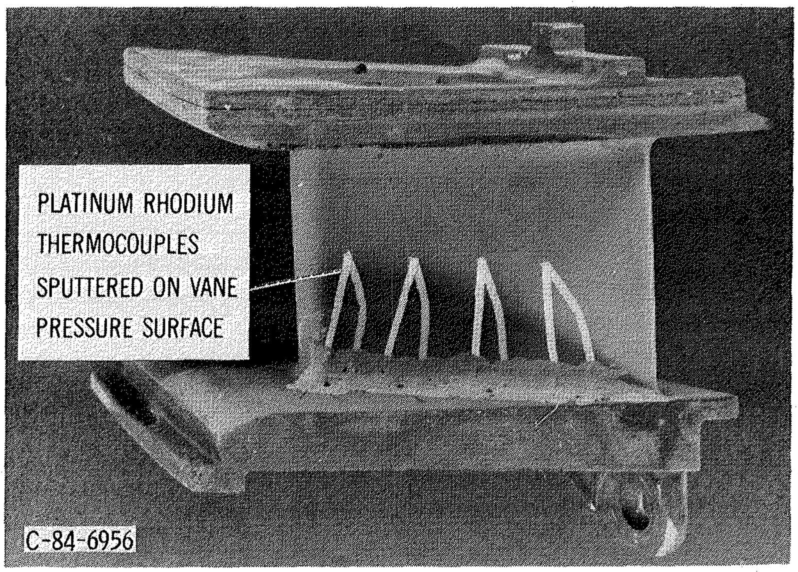

Figure 35. - Thin film thermocouple installation.

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15. Supplementary Notes

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16. Abstract

It is the purpose of this paper to discuss future directions in aeropropulsion technology that have been identified in a series of studies recently sponsored by the U.S. Government. Advanced vehicle concepts that could become possible by the turn of the century are presented along with some of their projected capabilities. Key "building-block" propulsion technologies that will contribute to making these vehicle concepts a reality are discussed along with projections of their status by the year 2000. Some pertinent highlights of the NASA aeropropulsion program are included in the discussion.

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